Field of Research in Sustainable Manufacturing

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Abstract Sustainability has raised significant attention in manufacturing research over the last decades and has become a significant driver of the development of innovative technologies and management concepts. The current chapter aims to provide a structured overview of the wide field of research in sustainable manufacturing with a particular focus on manufacturing technology and management. It intends to describe the role of manufacturing in sustainability, outline the complementary approaches necessary for a transition to sustainable manufacturing and specify the need for engaging in interdisciplinary research. Based on a literature review, it provides a structuring framework defining four complementary areas of research focussing on analysis, synthesis and transition solutions. The challenges of the four areas of research manufacturing technologies ("how things are produced"), product development ("what is being produced"), value creation networks ("in which organisational context") and global manufacturing impacts ("how to make a systemic change") are highlighted and illustrated with examples from current research initiatives.

1 The Role of Manufacturing in Sustainability

Humanity is increasingly confronted with the challenge of dealing with a finite earth—a world with a limited "carrying capacity" (Arrow et al. 1995) and with "planetary boundaries" (Rockström et al. 2009), with some expecting "limits to growth" (Meadows et al. 1972). Owing to the unprecedented growth in population and economic output experienced since the 19th century (respectively six and sixty-fold, Maddison 2006), the stress imposed by humanity on natural equilibria

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has reached alarming levels at the same time that it fortifies increasing inequality between early industrialised and emerging countries. The limited capacity of the atmosphere to take stock of the emissions produced by our carbon-based economies, poses a threat not only to natural equilibria, but also to our own daily conditions of living (Edenhofer et al. 2015). The flows of some elements due to human activities, such as phosphor and nitrogen, now exceed natural flows, thus threatening the balance of the metabolism of natural ecosystems (Vitousek et al. 1997). Hence, the risk of "overshooting", i.e. drawing on the world's resources faster than they can be restored, while releasing wastes and pollutants faster than the earth can absorb them, is very real and the ongoing, unresolved challenge of our time (Meadows et al. 2004).

Although the concept of "sustainable development" (as defined for example by Brundtland et al. 1987) has received significant attention and motivated numerous initiatives in favour of, e.g. recycling, energy efficiency, the need for action is now nevertheless greater than ever before. This is particularly underscored by the observation that, despite international efforts to combat climate change, the global energy system is carbonizing due to a global renaissance of coal (Steckel et al. 2015). Further and more innovative decarbonisation solutions are therefore urgently needed.

As a major stakeholder in several areas of human living, industry has a great role to play in sustainability. It first contributes significantly to the overall environmental impact of human activity. It represents 26 % of the final energy consumption in the EU 27 (Lapillonne et al. 2013, data from 2013), emits 28.5 % of the greenhouse gases produced in the EU 27 (European Commission 2013) and uses energy which is still generated from fossil energy sources by up to 56 % (Lapillonne et al. 2013, data from 2013). In 2006, the European Commission estimated an overall European energy saving potential of 20 %. In the case of industries, the potential savings are estimated to be 25 %, representing annual losses of about 100 billion euros (European Commission 2006). At the same time, while the precision of production processes reaches ever smaller scales, the energy consumption of corresponding production systems is increasing exponentially (Gutowski et al. 2011). Meanwhile, further increases in energy consumption are anticipated.

Beyond its direct environmental impacts, the discrete product manufacturing sector also influences the resource consumption of its products over their entire lifecycle, and therein plays a critical and complex role in sustainability (Duflou et al. 2012). This role is particularly relevant considering that households in early industrialised countries face a literal "rise of the machines" and are equipped with more products and appliances than only a few decades ago (Energy Saving Trust 2006). The average household in early industrialised countries may own thousands of material items, so managing the volume of the possessions becomes a stress factor (Arnold et al. 2012).

With respect to the social aspects, the industrial sector employs 17 % of the European workforce (Eurofound 2012) and represents more than 23 % of worldwide total employment (International Labour Organization 2014). On the other hand, while working conditions in the manufacturing sector have improved steadily over the last decades (World Health Organization 2013), poor working conditions persist in resulting in as many as 300,000 work-related deaths and economic losses of 4 % of the gross domestic product of the European region every single year (WHO 2016). Globally, industries are responsible for 7.2 % of child labour, or 12 million people (Diallo et al. 2013).

That said, manufacturing stands strong as a crucial sector for the development of economies. Manufacturing generates 14 % of the gross domestic product (GDP) of OECD countries and of Europe according to the OECD (2016),[1] and 31 % of the world GDP according to the US central intelligence agency (2016).[2] Beyond this quantitative contribution to the GDP, whose reflection of actual wealth is debatable (see e.g. Costanza et al. 2014), it has been shown that stable specific and sequential sectoral patterns can be observed in economic development processes across the spectrum of countries, with specific manufacturing sectors furthermore playing an important role in initializing economic development processes in poor countries (Radebach et al. 2014). On the whole, thus, basic manufacturing activities seem to be a necessary enabler for the development of modern economies.

To summarize, manufacturing as a subset of the industrial sector (see glossary for disambiguation of the terms) has a threefold impact on sustainability:

- it plays a major role in the creation of wealth;
- it directly contributes to the material metabolism of human societies as it requires material input and produces outputs;
- it indirectly contributes to the material metabolism of human societies as it produces outputs having their own metabolism even after having left manufacturing systems.

2 Existing Approaches of Sustainable Manufacturing

As a counterpoint to this tripartite observation, sustainable manufacturing is defined in the present publication as (see also the glossary for more information on this definition):

> creation of discrete manufactured products that in fulfilling their functionality over their entire life cycle cause a manageable amount of impacts on the environment (nature and society) while delivering economic and societal value.

The international research community has been particularly active in the last decades in the development of conceptual or concrete solutions toward sustainable manufacturing (see for example Arena et al. 2009). The objective of the current contribution is to deliver a framework for providing a structured overview of the existing field of research in sustainable manufacturing, with a particular focus on industrial engineering. It intends to outline the complementary approaches required

[1]Accessed 09.03.2016. Figures for EU-28/2015 and for OECD/2014.

[2]Accessed 22.08.2016, last updated 04.02.2016.

for a transition to sustainable manufacturing and their necessary interdisciplinary modus operandi. While Sect. 2.1 provides an overview of previous attempts in this direction, Sect. 2.2 introduces an original framework of sustainable manufacturing, according to which the present book publication is structured. Section 3 is specifically dedicated to the discussion of the challenges of multi-, inter- and transdisciplinary approaches faced by researchers in sustainable manufacturing.

2.1 Review of Published Frameworks

Since the emergence of the first initiatives explicitly termed as green engineering or sustainable manufacturing, several reviews of the field have been undertaken and frameworks have been proposed that identify the complementary areas of research that need to be addressed. Jayal et al. (2010), for example, deliver an overview of strategies for sustainable manufacturing with a particular focus on the modelling and assessment techniques for the development of sustainable products, processes and supply chains. Duflou et al. (2012) provide an extensive review of strategies for energy and resource efficiency in discrete part manufacturing, considering five complementary levers: unit process, manufacturing line, facility, manufacturing system and global supply chain. Based on the evaluation of the potential of these techniques, they estimate potential energy savings of 50 % in the overall consumption in the manufacturing sector. Garetti and Taisch (2012) furthermore published an overview of trends affecting the manufacturing sector, highlighting the challenges raised by sustainability in this sector and the corresponding strategies. They identify four complementary research clusters with a broader focus: enabling technologies, resources and energy management, asset and product lifecycle management, business model and processes. Finally, Haapala et al. (2013) made recommendations for further research on sustainable manufacturing, based on the review of existing initiatives and considering two foci: manufacturing processes and equipment along with manufacturing systems.

It is worth noting that all these reviews identify both sustainability assessment methods and technical strategies (*analysis* and *synthesis*) as necessary and complementary approaches to sustainable manufacturing. Analytical approaches are required in order to put words and figures to the problems which may ultimately be solved by synthesis. One example of this is found in the inventory of approaches for energy efficient manufacturing at the unit process level given by Duflou et al. (2012), where data acquisition, computational models and energy assessment methods stand alongside technical solutions such as "technological change" or "waste recovery within the machine tool." Two of the four publications go further, and state that analysis and synthesis approaches can only be effective if enabled by adapted *education* tactics. On one side of the equation, a systematic implementation of analysis and synthesis approaches in industry requires that engineers fully appreciate the sustainable manufacturing concepts and are trained in multi-objective decision-making. On the other side, the general public can only foster sustainable production if they fully appreciate the impact of their consumption patterns.

While such reviews identify different yet overlapping scopes, the sustainable manufacturing solutions they identify can be classified into four different areas, which we will call for our purposes *layers*:

- Manufacturing technologies: approaches focused on "how things are manufactured", i.e. whose object of research lies in processes and equipment, including machine-tools or facilities. Examples of such approaches are among other things: development of new or improved manufacturing processes, predictive maintenance of production equipment, determination of process resource consumption, process chain simulation, or energy-efficient facility building.
- Product lifecycles: approaches focussed on "what is to be produced", i.e. whose object of research is the product definition (where product can be understood as a good or a service). Examples of such approaches are among others: asset and product lifecycle management, intelligent product, simplified product sustainability assessment.
- Value creation networks: approaches focused on the organisational context of manufacturing activities, i.e. whose objects of research are organisations such as companies or manufacturing networks. Examples of such approaches are among others: resource efficient supply chain planning, industrial ecology.
- Global manufacturing impact: approaches focused on the transition mechanisms towards sustainable manufacturing, i.e. whose objects exceed the conventional scope of engineering. Examples of such approaches are among others: development of sustainability assessment methods, education and competence development, development of standards.

Table 1 summarizes how the four cited reviews of the field of sustainable manufacturing correspond to the four identified layers.

Table 1 Four layers of sustainable manufacturing identified in previous frameworks

Layer	Object addressed	Haapala et al. (2013)	Garetti and Taisch (2012)	Duflou et al. (2012)	Jayal et al. (2010)
Global manufacturing impact	World (society, environment, economy)	•	•		
Value creation networks	Organisations (companies and manufacturing networks)	•	•	•	•
Product lifecycles	Product definition (good and service)		•		•
Manufacturing technologies	Process and equipment (machine-tool, facility)	•	•	•	•

As a last observation, it should be noted that although these reviews define sustainable manufacturing as resulting from the consideration of the three dimensions, the specific solutions which they present remain confined to the environmental dimension (or even consider resource efficiency exclusively) and in so doing, elude the social dimension altogether. This is in accordance with the observation provided by Arena et al. in 2009 already, in their extensive state-of-the-art of industrial sustainability study: while the social dimension of sustainability is generally viewed to be worth considering, only few specific solutions have been provided to date which address these social issues. In their summary of published research on the role of manufacturing in social sustainability, Sutherland et al. (2016) state that manufacturing enterprise still lacks standardised approaches for internalising social sustainability and for outlining directions of future work in order to mitigate this situation, such as the further development of Social Life Cycle Assessment (S-LCA).

Based on these contributions and the observations made, the next section introduces a framework structuring the field of the necessary research for enabling the transition to sustainable manufacturing.

2.2 Proposed Framework

Manufacturing activities can be characterised as the interplay of five value creation factors, i.e. human, process, equipment, organisation and product, taking place in value creation modules (Seliger et al. 2011). Value creation modules are, in turn, vertically and horizontally integrated into geographically distributed value creation networks. Value creation modules generate effects on the three dimensions of sustainability that can be measured by sustainability assessment methods.

Following the value creation network model depicted in Fig. 1 and based on the findings of the previous section, sustainable manufacturing can be defined as the necessary interplay of three kinds of approaches:

- analysis approaches, i.e. methods allowing the evaluation of value creation based on the three dimensions of sustainability;
- synthesis approaches, i.e. implementation of these methods in the development of technical systems at all levels of value creation (value creation factors, modules and networks);
- approaches for systemic changes, i.e. to transform business to become standard vehicles towards sustainable processes; in other words: enabling the systematic integration of sustainability in day-to-day decision-making.

These approaches are embedded in the four concentric and sequentially including areas introduced in the previous section: manufacturing technologies, product lifecycle, value creation networks, global manufacturing impact. The interplay of analysis, synthesis and transition approaches and these four layers are

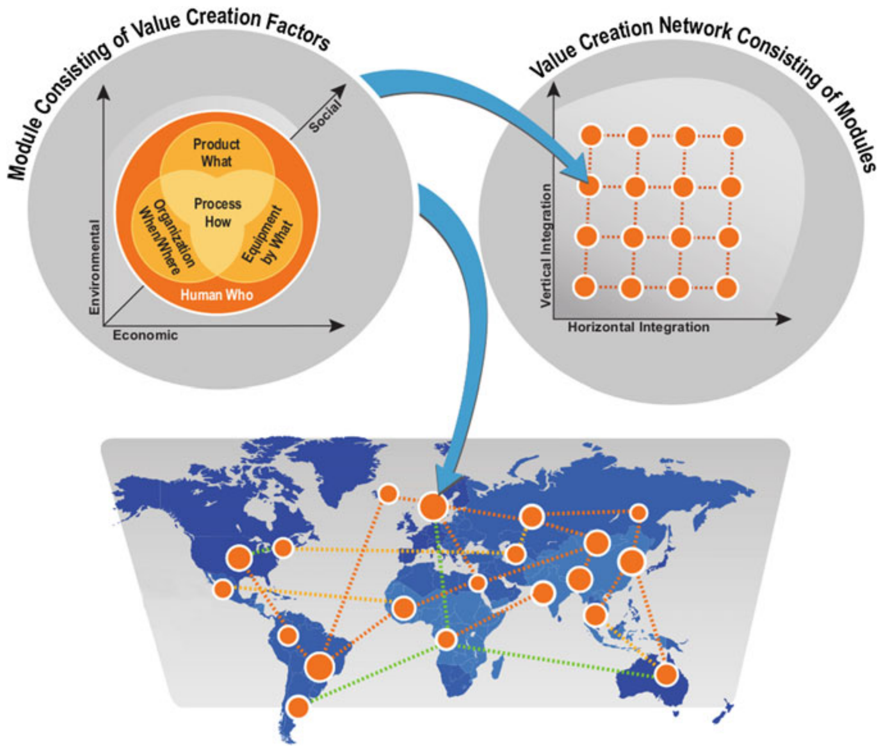

Fig. 1 Value creation network (VCN) model

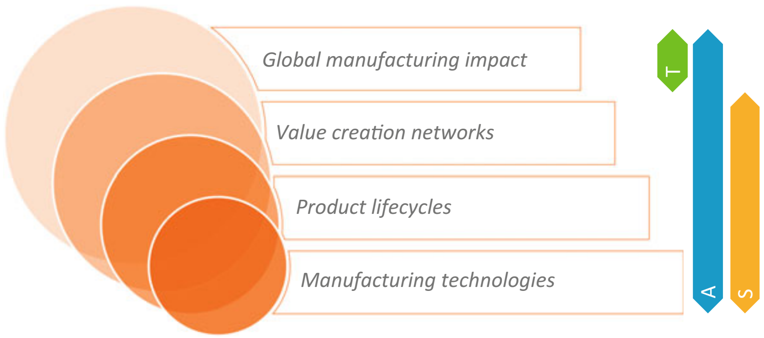

Fig. 2 Interplay of analysis, synthesis and transition approaches and the four areas of sustainable manufacturing (*T* transition; *A* analysis; *S* synthesis)

depicted in Fig. 2 while Table 2 presents their respective scientific disciplines and objects of research. Layers are depicted with more detail in the subsequent sections of this chapter.

Table 2 Objects and scientific disciplines of the four layers of sustainable manufacturing

Layer	Object addressed	Discipline concerned
Manufacturing technology	Process and equipment (machine-tool, facility)	Production engineering, factory planning, operation management
Product development	Product definition (good and service)	Engineering design
Value creation networks	Organisations (companies and manufacturing networks)	Business economics, knowledge management
Global manufacturing impact	World (society, environment, economy)	Micro and macro-economics, natural sciences, humanities, politics, education

2.3 Manufacturing Technologies

This layer specifically addresses the two factors of value creation *process* and *equipment*. It focuses on the development of production technologies, machine-tool concepts and factory management techniques ensuring that whatever has to be produced, it can be done with economy of resources which likewise uphold social standards.

This first requires determining specific indicators which enable the identification of improvement potential at the process and at the machine level. Examples of these are found in the "specific energy consumption," an empiric model developed by Kara and Li (2011) for material removal processes and based on measures on machine tools, or the "electrical deposition efficiency," an analytic model developed by Sproesser et al. (2016) for welding processes. At facility level, cyber-physical systems (Low et al. 2005) and metering techniques (Kara et al. 2011) can be employed in tandem with appropriate facility models and simulation techniques (e.g. Herrmann and Thiede 2009) in order to enable optimal steering of processes within a manufacturing system.

Regarding the development of new technologies, existing efforts encompass, for example, the improvement of welding technologies in terms of resource consumption (Sproesser et al. 2015) or the development of new internally cooled cutting processes (Uhlmann et al. 2012). At the manufacturing cell level, lifetime-extending add-ons for machine-tools (Kianinejad et al. 2016) and of automated workplaces preventing musculoskeletal strain by workers (Krüger and Nguyen 2015), can be cited as examples.

While such solutions form a necessary basis for sustainable manufacturing, macroeconomic calculations underscore that applying best available sectorial technologies in all regional industry sectors across the world would reduce CO_2 emissions to one-third (Ward et al. 2015). This shows that solutions are required beyond the manufacturing technology level in order to reach e.g. the factor 4 or 10 pinned by some authors as a necessary objective of environmental reduction of human activities (e.g. Weizsacker 1998).

This layer is specifically addressed in the part "Solutions—Sustainability-driven Development of Manufacturing Technologies" of the present book.

2.4 Product Lifecycles

This layer specifically addresses the factor of value creation *product*. It focuses on enabling the operation of product development processes systematically leading to products which achieve balance of the three dimensions of sustainability, i.e. which generate low environmental impacts while delivering socially useful functions, all available at reasonable production and purchase prices. This requires the application of methods allowing product development teams to systematically integrate sustainability criteria into their decisions.

Over the past decades, a large variety of methods of this type have been developed. As early as 2002, Baumann et al. identified more than 150 methods for "green product development", i.e. focusing strictly on the environmental dimension of sustainability, while Pigosso (2012) more recently identified 106 of them. The wide range of methods generated by the scientific community led Ernzer and Birkhofer (2002) to state that the difficulty no longer lies in developing design methods, but lies rather in selecting the relevant methods and applying them efficiently. As a matter of fact, existing methodological support for sustainable product development is often criticized for being poorly integrated into the product development process, ultimately leading to additional exertion on the part of product development engineers, and at the same time to low industry diffusion (Rosen and Kishawy 2012; Knight and Jenkins 2009).

Addressing this very issue, Pigosso et al. (2013) developed a maturity model which allows a step-by-step, guided integration of sustainable product development methods in companies. At a more operational level, Buchert et al. (2014) developed an IT-tool aimed at supporting the selection of the appropriate method for a given design problem. From the flipside of the process, some other authors have striven to reduce the diversity of tools through the development of integrated frameworks (e.g. Dufrene et al. 2013). In all cases, a key factor for effective consideration of sustainability in daily product development activities is found in the integration of methods in information systems such as Product Lifecycle Management (Stark and Pförtner 2015).

Given the high number of constraints applying to product development which limit the solution space spectrum along with the attainable level of innovation, parts of the research community have striven to reclaim degrees of freedom in their pursuits, by fostering alternative production or consumption patterns. A well-researched topic in this area is found in the concept of product service systems through which: "it is in the economic and competitive interest of the producer/provider to foster continuous innovation in reducing the environmental impacts and improving social equity and cohesion" (Vezzoli et al. 2015). Another partially overlapping field of research is found in the participative design models allowing for a deeper integration of the voice of the final user in the design process, such as user-centred design or open source design (Aitamurto et al. 2015; Bonvoisin and Boujut 2015).

This layer is specifically addressed in the part "Solutions—Sustainable Product Development" of the present book.

2.5 Value Creation Networks

This layer addresses the value creation factor *organisation* as well as the combination of value creation modules into value creation networks. It addresses the ability of the value creation networks to support sustainable production and products. How sustainable a product proves to be, may, for instance, be determined not only by its design, but also by an array of choices made in the value creation network that are not accessible to the product development team. More specifically, a given product cannot be claimed to be sustainable universally or inevitably, but in relation to a given context and associated use (Manzini and Jégou 2003). The remanufacturability of a product, furthermore, only constitutes potential that is born out of the product design itself, and can only be realized by the interplay of activities including, among other things, reverse logistics, product dismantling and testing. How sustainable a transportation system based on electric cars proves to be for a given area, for example, may depend on the density of the population and the existence of an appropriate public transportation network. Following Haapala et al. (2013) in that pursuit, then, the question lies not only in which processes are performed, but also *where* these processes are performed. This question is notably important in a world of globalized supply chains where intensive processes tend to be outsourced to emerging countries (Andersson and Lindroth 2001; Bonvoisin 2012).

Taking this into consideration, approaches are required to help ensure the development of organisational infrastructure which facilitates sustainable products and productions. Two critical aspects identified by Jayal et al. (2010) are multi-objective and integrated value creation planning. One challenge lies in moving from the coordination of independently managed organisations with individual profit maximisation behaviour, to more integrated planning. The other challenge is to go beyond profit minimisation and integrate several dimensions into the decision-making process in pursuit of connecting value creation modules.

This layer is specifically addressed in the part "Solutions—Sustainable Value Creation Networks" of the present book.

2.6 Global Manufacturing Impact

This last layer addresses the penetration rate of sustainable solutions, i.e. how far sustainable decision-making methods are implemented in practice. In order to pave the way for necessary cultural change, research which takes on the triple role of yardstick (measuring sustainability), guidepost (setting targets) and multiplier (motivating towards a direction), is what is required.

The first role requires the development of methods for measuring the actual sustainability performance of products and manufacturing activities, examining improvement potentials and identifying trade-offs between the achievement of multiple targets. As a central methodology in sustainable engineering, Life Cycle Assessment (LCA) and even more relevant, Life Cycle Sustainability Assessment (LCSA) (Finkbeiner et al. 2010), figure as essential parts of the solution. These tools however represent heavy machinery that remain too time-consuming and difficult for engineers to appreciate, and therefore hardly applicable in day-to-day decision-making. In particular, a first task lies in equipping engineers with the knowledge and framework of reference necessary to select appropriate indicators among the huge amount of indicators available. A second predicament underlined by Jaya et al. (2010) lies in the development of rapid and convenient sustainability evaluation procedures which yield results as precise as LCA.

The second role requires the development of methods for setting appropriate sustainability targets. For example, most LCA indicators (e.g. global warming potential) have been primarily developed for determining the sustainability performance of a product or process in comparative terms (i.e. in comparison with another product or process delivering the same function). Hence, they can support manufacturing that always strives to "be more sustainable than before" but cannot ensure that manufacturing is sustainable in absolute terms (Bjørn and Hauschild 2013). Yet, despite however useful they may be for comparing processes or products, these indicators need to be complemented by a sustainability analysis in more absolute terms. This includes both the setting of clear sustainability reference values/targets (e.g. maximum allowed CO_2 emissions to meet the 2° goal) and the development of methods to analyse the sustainability of products and processes with regard to these targets (as proposed by Bjørn et al. 2016, for example).

The third role involves the overall effort attached to the information transfer to industry, policymakers and the general public, in order to stimulate the necessary cultural change. One essential lever in that pursuit advocated by Haapala et al. (2013), Mihelcic et al. (2003) and Garetti and Taisch (2012) is non other than pure and simple education. On the one hand, manufacturing-related curricula should provide engineers with a broader understanding of the concept of sustainability and of the influence of their activities on societal and environmental systems. They should be able to identify improvement potential in technical systems towards sustainability, evaluate optimal solutions, and take decisions accordingly. At the same time, they should be made to appreciate the socio-technical nature of sustainable manufacturing, along with the influence of the behaviour of consumers and users on the other side of the spectrum. On the other hand, the actual transition towards sustainability not only relies on engineers, but also on the "environmental" and "technological literacy" (Mihelcic et al. 2003) of the greater citizenry, which would allow people to make enlightened and balanced consumer decisions. Considering empirical observations showing that both concepts of sustainability and manufacturing may not generally be well understood (e.g. Roeder et al. 2016), a tremendous need is present for the integration of all such concerns in education agendas, from primary school to university.

This layer is specifically addressed in the part "Implementation Perspectives" of the present book.

3 Challenges of Interdisciplinarity in Sustainability Research

The above detailed layers are not only complementary on the topics which they address, but likewise interdependent. Stock and Burton (2011) note that sustainability "necessitate[s] solutions informed by multiple backgrounds that singular disciplines seem unable to provide, and possibly, are even incapable of providing" and therein they underline the necessity for collaboration between the disciplines. They differentiate between multi- and interdisciplinarity: while multidisciplinarity is characterized by the co-existence of different scientific disciplines with parallel objectives in a common research field, interdisciplinarity seeks to bridge disciplinary gaps in perspective by involving different disciplines in the achievement of a common goal. Together with Schäfer (2013), they even advocate for transdisciplinary research, i.e. the inclusion of non-researcher stakeholders such as representatives from enterprises, administration or NGOs, end-users or citizens in the process of producing solutions of complex socio-technical problems. One argument for this is that the very concept of sustainability cannot be stated universally, but instead has to be considered within each and every specific social context. This requirement is backed by the strong observation stressed by Mihelcic et al. already in 2003 that engineering disciplines lack connective oversight of societal problems, that the public has difficulty appreciating what exactly engineers do, and that engineers tend to overlook the social dimension attached to the socio-technical problems which they invariably address. A further tendency to isolation of engineering disciplines, furthermore, generates a risk of drifting towards what has been already criticized by thinkers of the technological society such as Ellul (1964) or Illich (1982), and referred to as "second order problems" in the sustainability debate. That is, strictly technical solutions to sociotechnical problems serve to increase technicisation and generate new socio-technological problems in a headlong rush, serving ultimately to worsen the situation that is supposed to be mitigated. One typical example of the result of such processes is the often cited "rebound effect," defined for example by Hertwich (2005) in an industrial ecology perspective as “a behavioural or other systemic response to a measure taken to reduce environmental impacts that offsets the effect of the measure.” The problem thus lies in the propensity of engineers to develop one-sided technological solutions, or, better said, the general tendency on the part of engineering disciplines to “generate clever solutions for problems that do not exist.” Overcoming this problem thus figures hugely in the pursuit of sustainable manufacturing solutions. Specifically, bridges have to be built between disciplines well-rehearsed in asking questions (e.g. humanities) and disciplines adept in developing solutions (e.g. engineering).

Unfortunately, inter- and transdisciplinarity approaches in research remain ridden with obstacles. The major challenges of such approaches are highlighted for example by Schäfer (2013):

- Researchers should be open to broadening their horizons, i.e. acknowledging that collaboration with other disciplines gives them opportunities to address questions that are not accessible within the framework of their own discipline. For example, production technology engineers can develop cleaner production technologies with the help of environmentalists, allowing them to identify the relevant parameters. Empirical observations show that the lack of fulfilment of this basic requirement may be a significant reason for the failure of a large part of transdisciplinary projects.
- Disciplines should acknowledge the epistemic values and methods of other disciplines, which may prove to be particularly thorny between, for example, engineering and humanities—the former being generally based on positivist and the latter on constructivist epistemology.
- Considering that differentiation of technical terminology stands in the way of common understanding between disciplines, the fostering of common understanding requires the development of a common language. This requires in turn that researchers (1) acknowledge terms may have different meanings in their respective disciplines (2) consent to making the effort of identifying potential misunderstandings and defining the terms (3) avoid technical jargon in interdisciplinary exchanges.
- A barrier for openness of researchers towards inter- and transdisciplinarity might lie in the organisation of academia in highly specialized disciplines. In the context of the evaluation of research and allocation of research grants driven by discipline-related quality criteria, inter- and transdisciplinarity research may be disadvantaged.

Although the four difficulties cited here may sound trivial, experiences in major interdisciplinary research projects show that they are decisive indeed. Although convinced by the necessity of developing solutions for sustainability and by the complexity of the problem, researchers may well fail to cultivate interest in interdisciplinarity research and in broadening the focus of their activity. Literature on inter- and transdisciplinary sustainability research already gives some hints on how to address these challenges, that should indeed be more systematically taken into account in the planning and operation of research projects dealing with engineering and sustainability.

4 Conclusions

In this contribution, the current field of research in sustainable manufacturing has been screened, with a particular focus on technology and management. Based on this review, this article provides a definition of the term sustainable manufacturing as well as a structuring framework defining four complementary areas of research: manufacturing technologies ("how things are produced"), product development ("what is being produced"), value creation networks ("in which organisational context") and global manufacturing impacts ("how to make a systemic change"). These layers have been illustrated with examples from current research initiatives addressing analysis, synthesis or transition issues, while their respective principal challenges have been illuminated.

This article emphatically states the equal importance and the complementarity nature of these four layers, at the same time that we likewise underline the necessity of the interdisciplinary nature of action towards sustainable manufacturing. Since individual fields of expertise are unable to grasp the entire complexity of the challenges raised by sustainability, researchers are invited to consider the limits of the solutions they can offer, and to search for broadened perspectives beyond the frontiers of their expertise.

References

Aitamurto, Tanja, Dónal Holland, and Sofia Hussain. 2015. The open paradigm in design research. *Design Issues* 31(4): 17–29. doi:10.1162/DESI_a_00348.

Andersson, Jan Otto, and Mattias Lindroth. 2001. Ecologically unsustainable trade. *Ecological Economics* 37(1): 113–122. doi:10.1016/S0921-8009(00)00272-X.

Arena, Marika, Natalia Duque Ciceri, Sergio Terzi, Irene Bengo, Giovanni Azzone, and Marco Garetti. 2009. A state-of-the-art of industrial sustainability: Definitions, tools and metrics. *International Journal of Product Lifecycle Management* 4(1–3): 207–251. doi:10.1504/IJPLM.2009.031674.

Arnold, Jeanne E., Anthony P. Graesch, Enzo Ragazzini, and Elinor Ochs. 2012. *Life at home in the twenty-first century: 32 families open their doors*, 1st ed. Los Angeles: The Cotsen Institute of Archaeology Press.

Arrow, Kenneth, Bert Bolin, Robert Costanza, Partha Dasgupta, C.S. Carl Folke, Bengt-Owe Jansson Holling, et al. 1995. Economic growth, carrying capacity, and the environment. *Science* 268(5210): 520–521. doi:10.1126/science.268.5210.520.

Bjørn, Anders, and Michael Z. Hauschild. 2013. Absolute versus relative environmental sustainability. *Journal of Industrial Ecology* 17(2): 321–332. doi:10.1111/j.1530-9290.2012.00520.x.

Bjørn, Anders, Manuele Margni, Pierre-Olivier Roy, Cécile Bulle, and Michael Zwicky Hauschild. 2016. A proposal to measure absolute environmental sustainability in life cycle assessment. *Ecological Indicators* 63(April): 1–13. doi:10.1016/j.ecolind.2015.11.046.

Bonvoisin, Jérémy. 2012. *Environmental analysis and ecodesign of information services*. Université de Grenoble.

Bonvoisin, Jérémy, and Jean-François Boujut. 2015. Open design platforms for open source product development: current state and requirements. In *Proceedings of the 20th international conference on engineering design (ICED 15), 8—Innovation and Creativity, 11–22. Milan, Italy*.

Brundtland, Gru, Mansour Khalid, Susanna Agnelli, Sali Al-Athel, Bernard Chidzero, Lamina Fadika, Volker Hauff, et al. 1987. *Our common future*. Oxford University Press.

Buchert, Tom, Alexander Kaluza, Friedrich A. Halstenberg, Kai Lindow, Haygazun Hayka, and Rainer Stark. 2014. Enabling product development engineers to select and combine methods for sustainable design. In *Procedia CIRP*, *21st CIRP Conference on Life Cycle Engineering, 15 (January):* 413–18. doi:10.1016/j.procir.2014.06.025.

Costanza, Robert, Ida Kubiszewski, Enrico Giovannini, Hunter Lovins, Jacqueline McGlade, Kate E. Pickett, Kristín Vala Ragnarsdóttir, Debra Roberts, Roberto De Vogli, and Richard Wilkinson. 2014. Development: Time to leave GDP behind. *Nature* 505(7483): 283–285. doi:10.1038/505283a.

Diallo, Yacouba, Alex Etienne, Farhad Mehran, and ILO International Programme on the Elimination of Child Labour. 2013. *Global Child Labour Trends 2008 to 2012*.

Duflou, Joost R., John W. Sutherland, David Dornfeld, Christoph Herrmann, Jack Jeswiet, Sami Kara, Michael Hauschild, and Karel Kellens. 2012. Towards energy and resource efficient manufacturing: a processes and systems approach. *CIRP Annals—Manufacturing Technology* 61(2): 587–609. doi:10.1016/j.cirp.2012.05.002.

Dufrene, Maud, Peggy Zwolinski, and Daniel Brissaud. 2013. An engineering platform to support a practical integrated eco-design methodology. *CIRP Annals—Manufacturing Technology* 62 (1): 131–134. doi:10.1016/j.cirp.2013.03.065.

Edenhofer, Ottmar, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, et al. (eds.). 2015. *IPCC, 2014: Summary for Policymakers. In Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Ellul, Jacques. 1964. *The technological society*. Translated by John Wilkinson: Vintage Books.

Energy Saving Trust. 2006. The rise of the machines—a review of energy using products in the home from the 1970s to today.

Ernzer, M., and H. Birkhofer. 2002. Selecting methods for life cycle design based on the needs of a company. In *DS 30: proceedings of DESIGN 2002, the 7th international design conference, Dubrovnik*.

Eurofound. 2012. *Fifth European working conditions Survey*. Luxembourg: Publications Office of the European Union.

European Commission. 2006. *COM(2006)545—action plan for energy efficiency: Realising the potential*.

European Commission. 2013. *EU energy in figures—statistical pocketbook 2013*.

Finkbeiner, Matthias, Erwin M. Schau, Annekatrin Lehmann, and Marzia Traverso. 2010. Towards life cycle sustainability assessment. *Sustainability* 2(10): 3309–3322. doi:10.3390/su2103309.

Garetti, Marco, and Marco Taisch. 2012. Sustainable manufacturing: Trends and research challenges. *Production Planning & Control* 23(2–3): 83–104. doi:10.1080/09537287.2011.591619.

Gutowski, Timothy G., Sahil Sahni, Avid Boustani, and Stephen C. Graves. 2011. Remanufacturing and energy savings. *Environmental Science and Technology* 45(10): 4540–4547. doi:10.1021/es102598b.

Haapala, Karl R., Fu Zhao, Jaime Camelio, John W. Sutherland, Steven J. Skerlos, David A. Dornfeld, I.S. Jawahir, Andres F. Clarens, and Jeremy L. Rickli. 2013. A review of engineering research in sustainable manufacturing. *Journal of Manufacturing Science and Engineering* 135 (4): 041013. doi:10.1115/1.4024040.

Herrmann, Christoph, and Sebastian Thiede. 2009. Process chain simulation to foster energy efficiency in manufacturing. *CIRP Journal of Manufacturing Science and Technology, Life Cycle Engineering* 1(4): 221–229. doi:10.1016/j.cirpj.2009.06.005.

Hertwich, Edgar G. 2005. Consumption and the rebound effect: An industrial ecology perspective. *Journal of Industrial Ecology* 9(1–2): 85–98. doi:10.1162/1088198054084635.

Illich, Ivan. 1982. *Medical nemesis: The expropriation of health*. New York: Pantheon.

International Labour Organization. 2014. *Global employment trends 2014—risk of a jobless recovery?*. Geneva: International Labour Office.

Jayal, A.D., F. Badurdeen, O.W. Dillon Jr., and I.S. Jawahir. 2010. Sustainable manufacturing: Modeling and optimization challenges at the product, process and system levels. Sustainable development of manufacturing systems. *CIRP Journal of Manufacturing Science and Technology* 2(3): 144–152. doi:10.1016/j.cirpj.2010.03.006.

Kara, S., G. Bogdanski, and W. Li. 2011. Electricity metering and monitoring in manufacturing systems. In *Glocalized solutions for sustainability in manufacturing*, ed. Jürgen Hesselbach and Christoph Herrmann, 1–10. Springer, Berlin. http://link.springer.com/chapter/10.1007/978-3-642-19692-8_1.

Kara, S., and W. Li. 2011. Unit process energy consumption models for material removal processes. *CIRP Annals—Manufacturing Technology* 60(1): 37–40. doi:10.1016/j.cirp.2011.03.018.

Kianinejad, K., S. Thom, S. Kushwaha, and E. Uhlmann. 2016. Add-on error compensation unit as sustainable solution for outdated milling machines. *Procedia CIRP* 40(January): 174–178. doi:10.1016/j.procir.2016.01.094.

Knight, Paul, and James O. Jenkins. 2009. Adopting and applying eco-design techniques: A practitioners perspective. *Journal of Cleaner Production* 17(5): 549–558. doi:10.1016/j.jclepro.2008.10.002.

Krüger, Jörg, and The Duy Nguyen. 2015. Automated vision-based live ergonomics analysis in assembly operations. *CIRP Annals—Manufacturing Technology* 64(1): 9–12. doi:10.1016/j.cirp.2015.04.046.

Lapillonne, Bruno, Karine Pollier, and Nehir Samci. 2013. Energy efficiency trends in the EU—lessons from the ODYSSEE MURE Project.

Low, Kay Soon, W.N.N. Win, and Meng Joo Er. 2005. Wireless sensor networks for industrial environments. In *International conference on computational intelligence for modelling, control and automation, 2005 and international conference on intelligent agents, web technologies and internet commerce*, 2:271–76. doi:10.1109/CIMCA.2005.1631480.

Maddison, Angus. 2006. *The world economy*. Paris: Organisation for Economic Co-operation and Development. http://www.oecd-ilibrary.org/content/book/9789264022621-en.

Manzini, Ezio, and François Jégou. 2003. Sustainable everyday. *Design Philosophy Papers*, no. 4.

Meadows, Donella H., Dennis L. Meadows, Jorgen Randers, and William W. Behrens. 1972. *Limits to growth*. Universe Books.

Meadows, Donella H., Jorgen Randers, and Dennis L. Meadows. 2004. *Limits to growth: The 30-year update*, 3rd ed. White River Junction, Vt: Chelsea Green Publishing.

Mihelcic, James R., John C. Crittenden, Mitchell J. Small, David R. Shonnard, David R. Hokanson, Qiong Zhang, Hui Chen, et al. 2003. Sustainability science and engineering: The emergence of a new metadiscipline. *Environmental Science & Technology* 37(23): 5314–5324. doi:10.1021/es034605h.

OECD.Stat. 2016. Gross domestic product (GDP)—Table B1G: gross value added at basic prices, total activity.

Pigosso, Daniela C.A., Henrique Rozenfeld, and Tim C. McAloone. 2013. Ecodesign maturity model: a management framework to support ecodesign implementation into manufacturing companies. *Journal of Cleaner Production* 59(November): 160–173. doi:10.1016/j.jclepro.2013.06.040.

Pigosso, Daniela Cristina Antelmi. 2012. Ecodesign maturity model: A framework to support companies in the selection and implementation of ecodesign practices. Text, Universidade de São Paulo. http://www.teses.usp.br/teses/disponiveis/18/18156/tde-10082012-105525/.

Radebach, Alexander, Hauke Schult, and Jan Christoph Steckel. 2014. On the importance of manufacturing sectors for sustainable development and growth. Lisbon, Portugal.

Rockström, Johan, Will Steffen, Kevin Noone, F. Åsa Persson, Stuart Chapin, Eric F. Lambin, Timothy M. Lenton, et al. 2009. A safe operating space for humanity. *Nature* 461(7263): 472–475. doi:10.1038/461472a.

Roeder, Ina, Matthias Scheibleger, and Rainer Stark. 2016. How to make people make a change—using social labelling for raising awareness on sustainable manufacturing. In *Procedia CIRP, 13th global conference on sustainable manufacturing – decoupling growth from resource use*, 40: 359–64. doi:10.1016/j.procir.2016.01.065.

Rosen, Marc A., and Hossam A. Kishawy. 2012. Sustainable manufacturing and design: Concepts, practices and needs. *Sustainability* 4(2): 154–174. doi:10.3390/su4020154.

Schäfer, Prof Dr Martina. 2013. Inter- und transdisziplinäre Nachhaltigkeitsforschung – Innovation durch Integration? In *Soziale Innovation und Nachhaltigkeit*, ed. Jana Rückert-John, 171–94. Innovation und Gesellschaft. Springer Fachmedien Wiesbaden. http://link.springer.com/chapter/10.1007/978-3-531-18974-1_10.

Seliger, Günther, Carsten Reise, and Pinar Bilge. 2011. Curriculum design for sustainable engineering-experiences from the international master program. In *Advances in sustainable manufacturing*, ed. Günther Seliger, Marwan M. K. Khraisheh, and I. S. Jawahir. Berlin, Heidelberg.

Sproesser, Gunther, Ya-Ju Chang, Andreas Pittner, Matthias Finkbeiner, and Michael Rethmeier. 2015. Life cycle assessment of welding technologies for thick metal plate welds. *Journal of Cleaner Production* 108, Part A: 46–53. doi:10.1016/j.jclepro.2015.06.121.

Sproesser, Gunther, Andreas Pittner, and Michael Rethmeier. 2016. Increasing performance and energy efficiency of gas metal arc welding by a high power tandem process. In *Procedia CIRP, 13th global conference on sustainable manufacturing—decoupling growth from resource use*, 40: 643–48. doi:10.1016/j.procir.2016.01.148.

Stark, Rainer, and Anne Pförtner. 2015. Integrating ontology into PLM-tools to improve sustainable product development. *CIRP Annals—Manufacturing Technology* 64(1): 157–160. doi:10.1016/j.cirp.2015.04.018.

Steckel, Jan Christoph, Ottmar Edenhofer, and Michael Jakob. 2015. What drives the renaissance of coal? In *Proceedings of the National Academy of Sciences (PNAS)* forthcoming.

Stock, Paul, and Rob J.F. Burton. 2011. Defining terms for integrated (multi-inter-trans-disciplinary) sustainability research. *Sustainability* 3(8): 1090–1113. doi:10.3390/su3081090.

Sutherland, John W., Justin S. Richter, Margot J. Hutchins, David Dornfeld, Rachel Dzombak, Jennifer Mangold, Stefanie Robinson, et al. 2016. The role of manufacturing in affecting the social dimension of sustainability. *CIRP Annals—Manufacturing Technology* 65(2): 689–712. doi:10.1016/j.cirp.2016.05.003.

Uhlmann, E., E. Fries, P. Fürstmann, and et al. 2012. Tool wear behaviour of internally cooled tools at different cooling liquid temperatures, 21–27. Istambul, Turkey.

US Central Intelligence Agency. 2016. The World Factbook 2016.

Vezzoli, Carlo, Fabrizio Ceschin, Jan Carel Diehl, and Cindy Kohtala. 2015. New design challenges to widely implement 'sustainable product–service systems.'" *Journal of Cleaner Production*, Special Volume: Why have "Sustainable Product-Service Systems" not been widely implemented? 97(June): 1–12. doi:10.1016/j.jclepro.2015.02.061.

Vitousek, Peter M., Harold A. Mooney, Jane Lubchenco, and Jerry M. Melillo. 1997. Human domination of earth's ecosystems. *Science* 277(5325): 494–499. doi:10.1126/science.277.5325.494.

Ward, Peter T., Alexander Radebach, Ingmar Vierhaus, A. Fügenschuh, and Jan Christoph Steckel. 2015. How existing technologies can contribute to reduce global emissions. Helsinki.

Weizsacker, Ernst U. von. 1998. *Factor four: Doubling wealth, halving resource use—a report to the Club of Rome*. Earthscan.

WHO. 2016. Occupational Health. *World Health Organisation—Regional Office for Europe*. April 12. http://www.euro.who.int/en/health-topics/environment-and-health/occupational-health.

World Health Organization. 2013. WHO Global Plan of Action on Workers' Health (2008-2017): Baseline for implementation—global country survey 2008/2009—executive summary and survey findings.